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## Spectral analysis of radargrams of the Martian subsurface to constrain scatterer sizes-Application to RoSPR/Zhurong and RIMFAX/Perseverance GPR data

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### Introduction :

In planetary sciences, accessing the subsurface is essential to fully understand the geological history of a given site. GPR (Ground Penetrating Radar) offers a way to investigate the subsurface in a non-destructive manner. So far, five GPR have investigated the subsurface of the Moon and Mars from the surface. RIMFAX GPR [1] onboard the Perseverance rover of NASA's Mars 2020 mission is still operating at Jezero crater and RoSPR [2] investigated the subsurface of Utopia Planitia along the traverse of Zhurong, the rover of the CNSA's Tianwen-1 mission. Both RIMFAX and RoSPR are ultra-wide band GPR ; RIMFAX is a Frequency Modulated Continuous Wave radar operating from 150 to 1200 MHz while RoSPR is equipped with two channels : which respectively operate in the 15-95 MHz (low frequency or LF channel) and the 450-2150 MHz (high frequency or HF channel) ranges. The next GPR to Mars should be WISDOM [5] onboard the Rosalind Franklin rover of the ESA's ExoMars mission [8]; it is designed to probe the subsurface at Oxia Planum at frequencies in the 0.5-3 GHz range.

Clear buried interfaces or resolvable large reflecting structures are probably the most easily interpretable features a GPR can detect in the subsurface. However, radargrams often display diffuse scattering in the subsurface volume rather than clear structures. As an example, the radargram acquired by RoSPR at Utopia Planitia on Mars points to the presence in the subsurface of two layers containing scatterers of different size or nature, but no clear interface [3]. Scattering signature was also observed in the lunar subsurface by the LPR (Lunar Penetrating Radar), and the typical size of heterogeneities in the lunar regolith has been constraint [4].

In this work we propose to apply on RoSPR and, to a lesser extent, RIMFAX data a method developed on WISDOM simulated data [5]. This method aims at statistically retrieving the typical size of buried heterogeneities or scatterers from scattered signals in radargrams. The RoSPR LF profile section selected as an example to illustrate the method is shown on Fig 1. The orange section is 280 m long and corresponds to the end of the profile published in [3] displaying unambiguous

scattering down to depths of 50 meters.

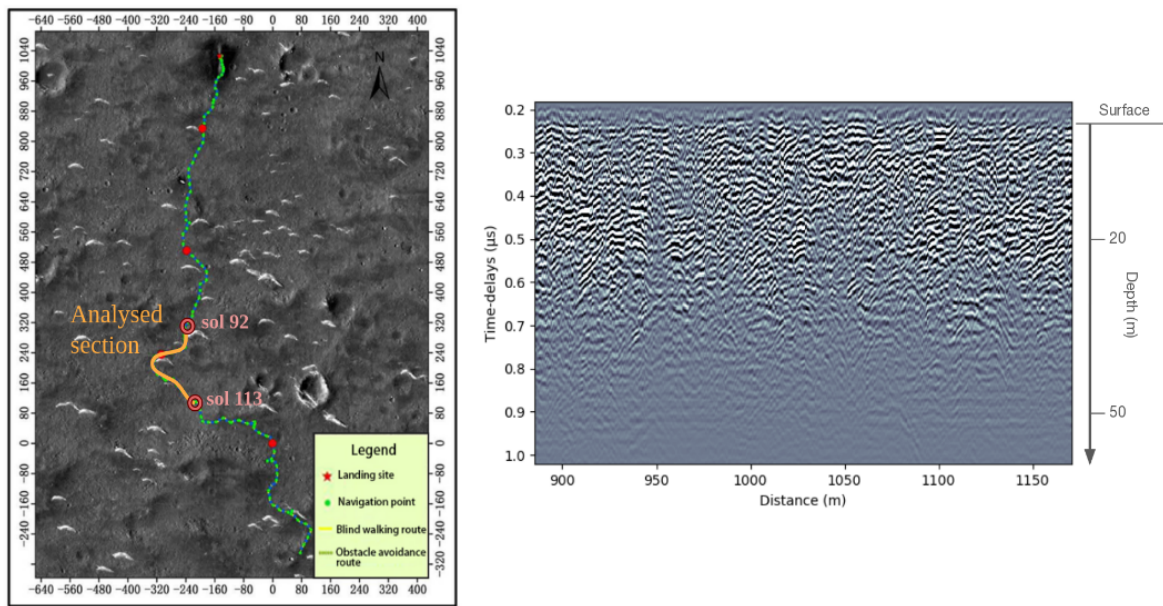


Figure 1: Left : Zhurong traverse from 25 May 2021 to 15 May 2022 (figure extracted and modified from [2]). Right : RoSPR Low-frequency channel radargram corresponding to the orange section on the map. The horizontal step is 25 cm.

### Method :

We conducted FDTD simulations with the TEMSI-FD code [6], that accurately models the WISDOM antennas in order to reproduce reliable soundings over 3-D synthetic heterogeneous media as illustrated by Fig 2. We generated a statistical number of subsurface volumes to perform meaningful statistical averages. Fig. 2 upper panel shows three examples of modelled subsurfaces with different typical size of scatterers  $L$ . Volume scattering occurs for each of the three  $L$  values considered, but the strongest volume scattering is not observed at the same frequencies. In other words, the wide frequency bandwidth of WISDOM allows to study the scattering process by sub-frequency bands to estimate the typical size of the buried structures. Fig. 3 synthesizes the results obtained with a sliding frequency window analysis for  $L$  values in the range 0.7-6.2 cm. A previous study [7] performed on simulated data shows that the maximum volume scattering intensity occurs for a wavelength  $\lambda = (5.3 \pm 0.2)L$  regardless of the value of  $L$ . We propose to use this result on Martian radargrams displaying diffuse scattering to constraint the  $L$  value in the investigated areas.

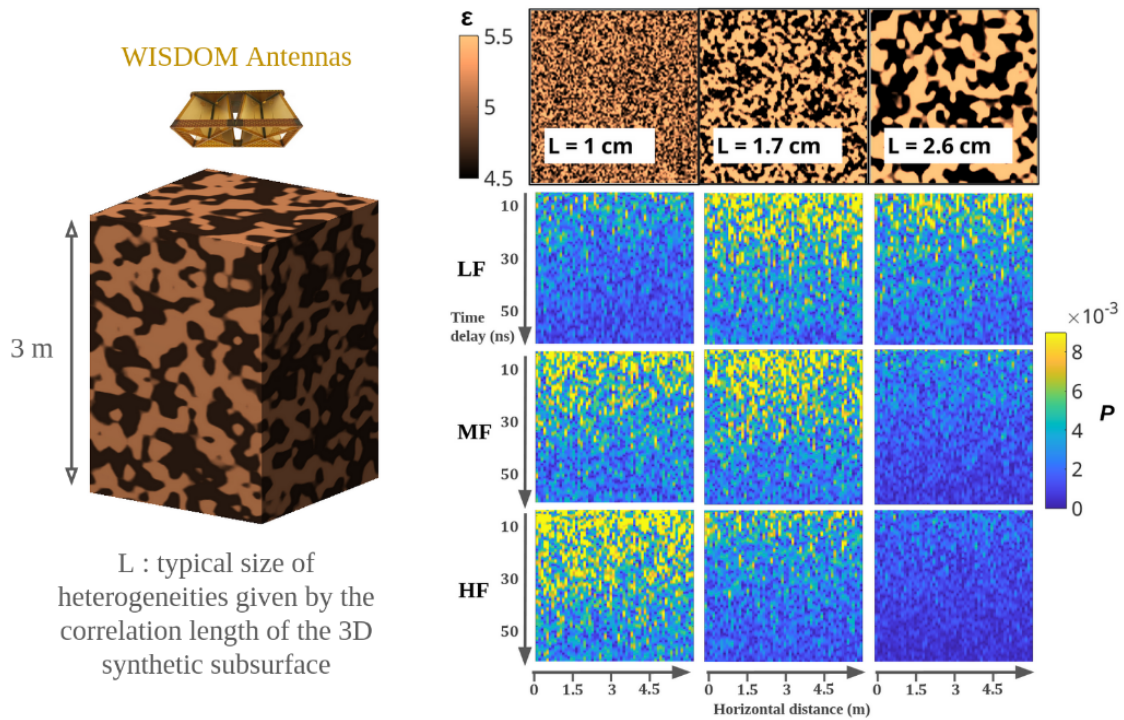


Figure 2 : Left : FDTD Simulations on synthetic 3-D heterogeneous media. Right : Illustration of the frequency dependency of the volume backscatter for 3 values of the typical size L of the heterogeneities. The analysis is performed for the whole range of delays in the radargrams.

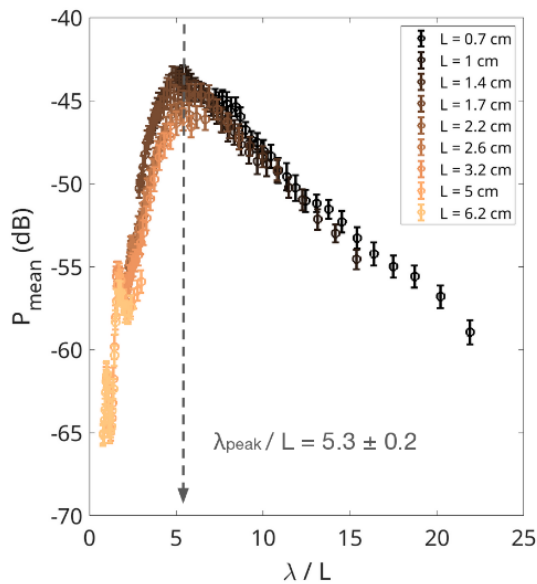
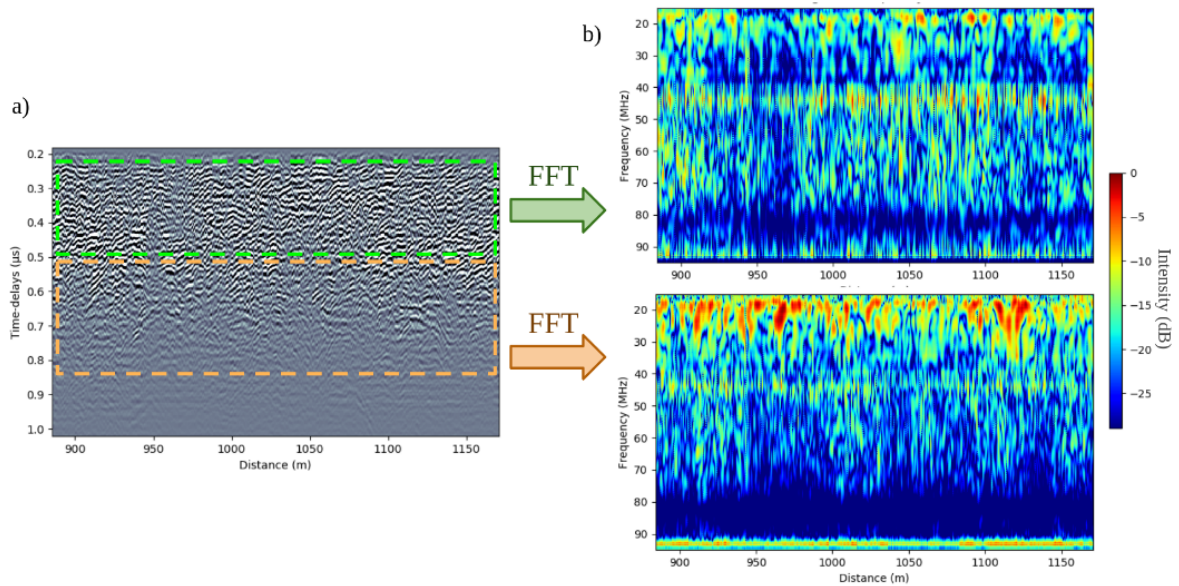


Figure 3 : Volume backscatter intensity as a function of  $\lambda/L$  for several typical size L. The fitted position of the global maximum is indicated.

We built spectrograms applying a Fourier Transform to have a quick and global picture of the frequency content along the profile. This can be done on selected time windows of the radargram

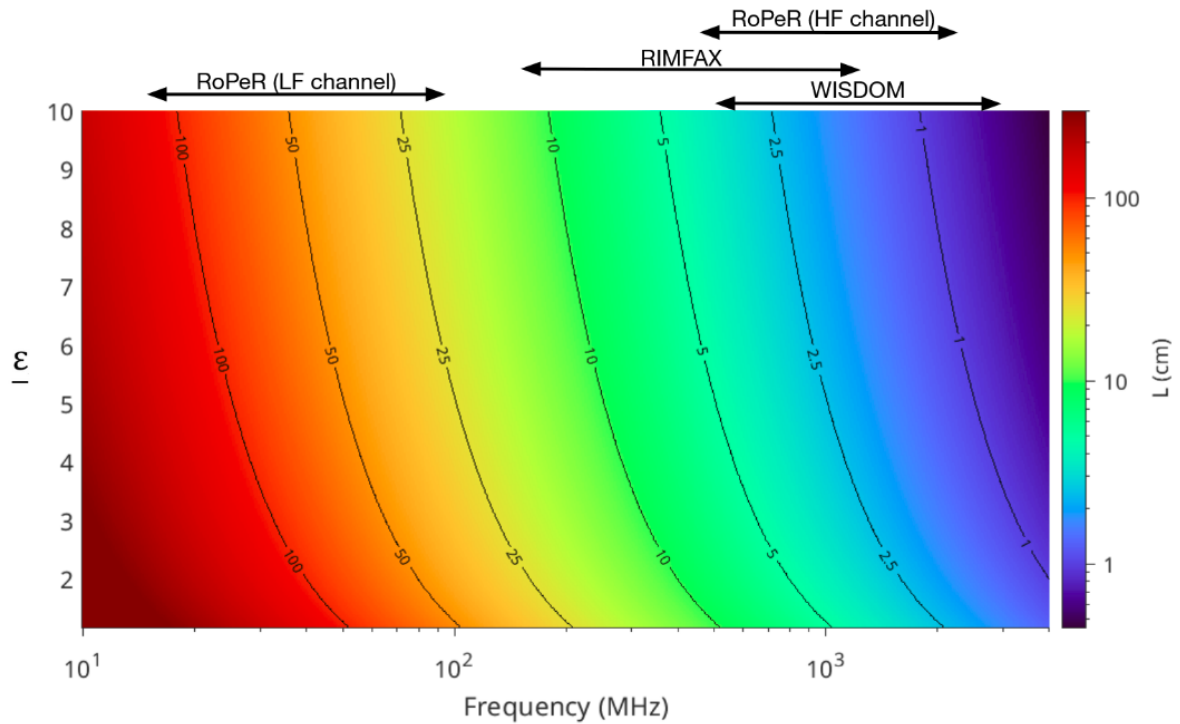
that correspond to given depth ranges (see Fig 4). This method also reveals possible horizontal variability in the frequency content of the radar signal. The described analysis requires in the first place to compensate the variability of the instrument's gain over the bandwidth . This is achieved by dividing the frequency domain data by the average RoSPR spectra of the subsurface of Utopia Planitia (a processing called whitening). However, in absence of proper calibration data, this correction is not perfect and some instrumental artifacts may remain (as it is the case on Fig. 4 around 47 and 84 MHz).



**Figure 4:** From a RoSPR LF radargram (a) to spectrograms (b). A window is applied in the time domain to investigate the frequency content at a given depth (here 0-20 m in green and 20-40 m in orange).

#### Results and preliminary analysis :

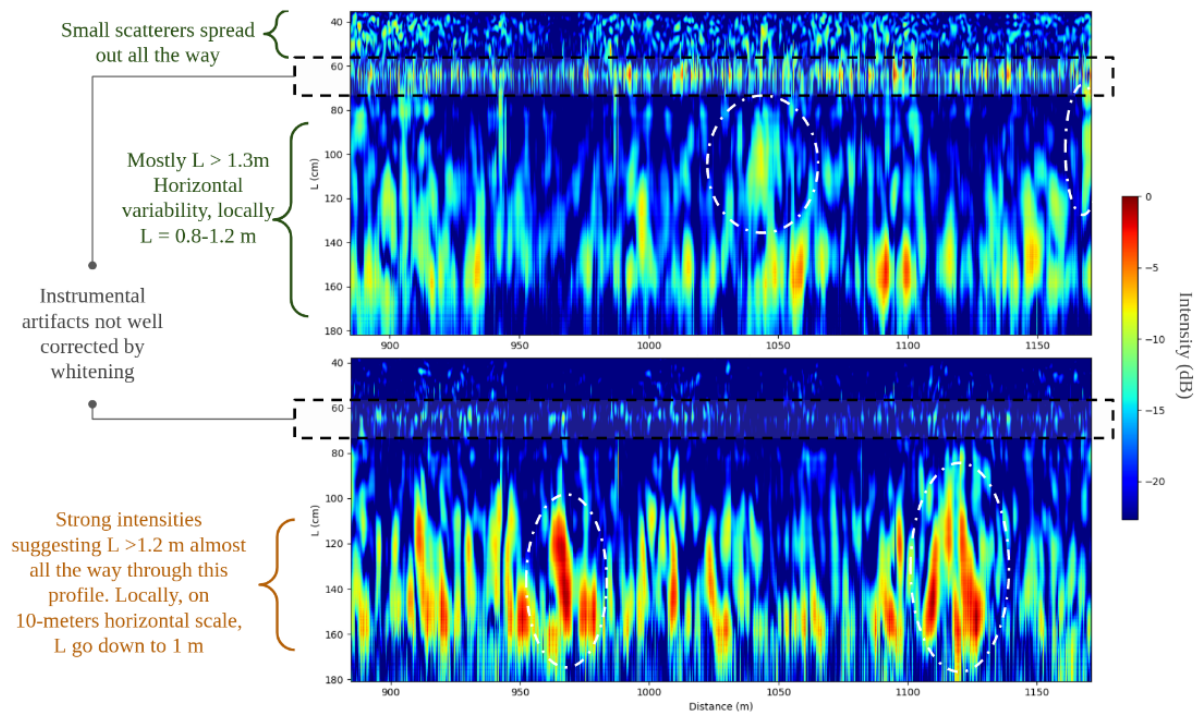
The result shown in Fig. 3 implies that ultra-wide band GPR data can be used to determine the size of heterogeneities within a range that depends on its frequency range of operation and of the average permittivity of the medium, as synthesized in Fig 5 for all Martian GPRs.



**Figure 5:** Map of the typical size  $L$  that can be retrieved as a function of the mean effective permittivity of the subsurface (vertical axis) and of the frequency of the GPR (horizontal axis). The frequency ranges of operation of the Martian GPR are indicated by the black arrows.

In Fig. 6 the spectrograms' frequency-axes corresponding to different time windows (Fig 4) are converted into  $L$ -axes via the relation established based on simulations (Fig. 3) in order to interpret them in terms of scatterer size. The main features are indicated in Fig 6, but must be taken with cautious. In particular, peaks in the volume scattering intensity can have various origins and only global maximums should be considered. Another caveat is the possible presence of several populations of scatterers of different sizes.

The difference between upper and lower maps in Fig. 6 somewhat supports the interpretation advanced by [3] with two layers characterized by smaller scatterers in the upper layer than in the lower layer). The spectrogram analysis method could put firmer constraints on their actual size distributions and horizontal scales of variability.



**Figure 6: Preliminary analysis of the spectrogram of Fig. 4.** Spectrogram vertical axis is now the typical size  $L$  of heterogeneities, horizontal axis is the distance covered by Zhurong rover. The upper map corresponds to the 200-500 ns time window (green dotted rectangle in Fig. 4) equivalent to 0-20 m depths (for  $\epsilon = 4.5$ ). The lower map corresponds to the 500 - 800 ns time window (orange dotted rectangle in Fig. 4) equivalent to 20-40 m depth. White dotted ellipses highlight main differences between the two spectrograms

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